REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY)*	**2. REPORT TYPE**	**3. DATES COVERED *(From – To)***
24 Jun 2015	Journal Article	Sep 2009 – Mar 2013

4. TITLE AND SUBTITLE

Reducing Secondary Insults in Traumatic Brain Injury

5a. CONTRACT NUMBER

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

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5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

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Aeromedical Research Department
2510 Fifth St.
Wright-Patterson AFB, OH 45433-7913

8. PERFORMING ORGANIZATION REPORT NUMBER

AFRL-SA-WP-JA-2015-0008

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSORING/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION / AVAILABILITY STATEMENT

Distribution A: Approved for public release; distribution is unlimited. Case Number: 88ABW-2015-0323, 29 Jan 2015

13. SUPPLEMENTARY NOTES

Published in Military Medicine, 180, 3:50, 2015

14. ABSTRACT

Objectives: To determine the alterations in intracranial pressure (ICP) during UF Air Force Critical Care Air transport Team transport of critically injured warriors with ICP monitoring by intraventricular catheter (IVC).
Methods: Patients with an IVC following traumatic brain injury requiring aeromedical evacuation from Bagram to Landstuhl Regional Medical Center were studied. A data logger monitored both ICP and arterial blood pressure and was equipped with an integral XYZ accelerometer to monitor movement.
Results: Eleven patients were studied with full collection of data from takeoff to landing. The number of instances of ICP > 20 mm Hg ranged from 0 to 238 and duration of instances ranged from 0 to 3,281 seconds. The number of instances of ICP ± 50% of the baseline ICP ranged from 0 to 921 and duration of instances ranged from 0 to 9,054 seconds. Five of the patients did not experience ICP > 20 mm Hg throughout their flight, but 10 patients showed instances of IC ± 50% of baseline ICP.
Conclusion: Patient movement results in changes in ICP both from external stimuli (vibration, noise) and from acceleration and deceleration forces. During transport, Critical Care Air transport Team crews should prioritize monitoring and correcting ICP including additional sedation and/or venting IVC.

15. SUBJECT TERMS

Traumatic brain injury, aeromedical transport, intracranial pressure, monitoring, hypoxia, hypotension

16. SECURITY CLASSIFICATION OF:			**17. LIMITATION OF ABSTRACT**	**18. NUMBER OF PAGES**	**19a. NAME OF RESPONSIBLE PERSON**
					Thomas Blakeman
a. REPORT	**b. ABSTRACT**	**c. THIS PAGE**			**19b. TELEPHONE NUMBER *(include area code)***
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Standard Form 298 (Rev. 8-98)
Prescribed by ANSI Std. Z39.18

MILITARY MEDICINE, 180, 3:50, 2015

Reducing Secondary Insults in Traumatic Brain Injury

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ABSTRACT Objectives: To determine the alterations in intracranial pressure (ICP) during U. S. Air Force Critical Care Air Transport Team transport of critically injured warriors with ICP monitoring by intraventricular catheter (IVC). Methods: Patients with an IVC following traumatic brain injury requiring aeromedical evacuation from Bagram to Landstuhl Regional Medical Center were studied A data logger monitored both ICP and arterial blood pressure and was equipped with an integral XYZ accelerometer to monitor movement. Results: Eleven patients were studied with full collection of data from takeoff to landing. The number of instances of ICP > 20 mm Hg ranged from 0 to 238 and duration of instances ranged from 0 to 3,281 seconds. The number of instances of ICP ± 50% of the baseline ICP ranged from 0 to 921 and duration of instances ranged from 0 to 9,054 seconds. Five of the patients did not experience ICP > 20 mm Hg throughout their flight, but 10 patients showed instances of ICP ± 50% of baseline ICP. Conclusion: Patient movement results in changes in ICP both from external stimuli (vibration, noise) and from acceleration and deceleration forces. During transport, Critical Care Air Transport Team crews should prioritize monitoring and correcting ICP including additional sedation and/or venting IVC.

INTRODUCTION

Traumatic brain injury (TBI) is recognized as the signature wound of the wars in Iraq and Afghanistan, imposing enormous costs on the quality of life in survivors and economic costs to the health system.[1–3] One of the major advances in military medicine during these wars has been the rapid evacuation of casualties to definitive care by the U.S. Air Force Critical Care Air Transport Teams (CCATT). However, there remain controversies regarding the appropriate time to fly the brain-injured patient and gaps in our knowledge related to the impact of hypobarism and acceleration/deceleration on intracranial pressure (ICP).[4–6] We hypothesized that secondary brain insults may occur frequently during en route care transport in patients with brain injury. We additionally hypothesized that automated data collection devices utilized during transport could more reliably document the frequency of these events and help us understand the causes. Understanding the causes will allow us to design processes to prevent these untoward events.

METHODS

The study was observational in nature and was approved by the U. S. Army Medical Research and Materiel Command Institutional Review Board (IRB), the University of Cincinnati IRB, and the Wright-Patterson Air Force Base IRB. This was a prospective study of data already being collected as a routine part of care. Patients with an intraventricular catheter for ICP monitoring requiring aeromedical transport from Afghanistan to Landstuhl Regional Medical Center in Germany were eligible for the study. The nature of the study precluded obtaining informed consent, so no patient identifiers or information from the medical record was collected.

We developed a datalogger for collection of ICP and blood pressure (if the patient had an indwelling arterial line). Standard physiologic pressure transducers were used (FloTrac, Edwards Lifesciences, Irvine, California). The dual output of the transducers allowed the routine monitoring of pressures using the CCATT standard Propaq monitoring and recording of the data to the data logger. The data logger (Fig. 1) which captured ICP, systolic, diastolic, and mean arterial pressure was mounted to the bed. As dictated by the electronic design of the data logger, all data points were routinely recorded to the data logger every 5 seconds. No patient identifiers were collected. The system also contained an x,y,z accelerometer to allow identification of takeoff and landing to determine the impact of acceleration and deceleration on ICP and blood pressure. Monitoring began when the patient was prepared for transport and included movement on the ambulance bus and in the aircraft. At the conclusion of the CCATT mission, the accumulated data fields stored in the data logger were downloaded to a conventional storage device and uploaded to a secure FTP site at the University of Cincinnati for subsequent analysis. Data analysis was conducted on the data streams saved to external software programs. Files were saved to the hard drive of a password-protected computer and reviewed retrospectively. Data analysis included identification of the number of events with ICP > 20 mm Hg and

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This article was presented in poster format at the Medical Health System Research Symoposium, Fort Lauderdale, Florida, August 13, 2013.

The views expressed in this article are those of the authors and do not necessarily represent the official position or policy of the U.S. Government, the Department of Defense, or the U.S. Air Force.

doi: 10.7205/MILMED-D-14-00381

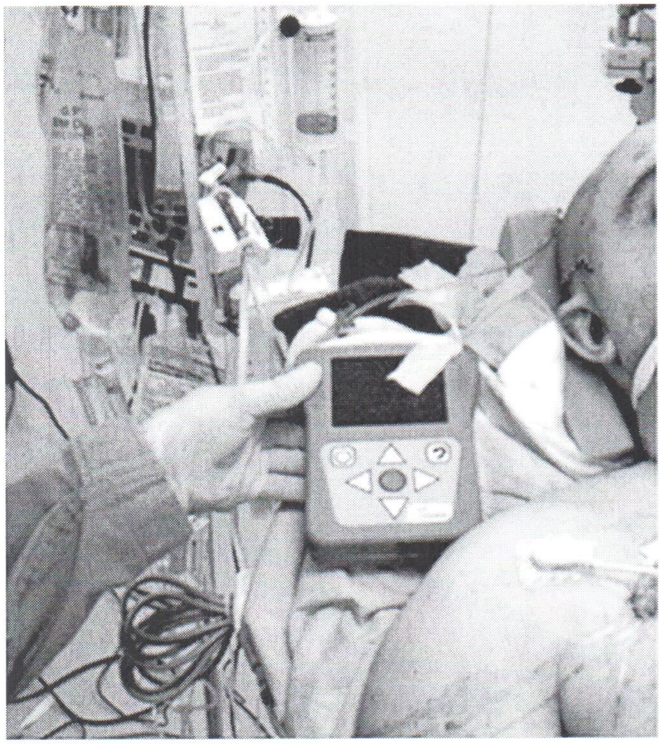

FIGURE 1. Data recorder.

the duration of these events. We evaluated changes in ICP with times for takeoff and landing for the specific aircraft used on that day for transport. The effects of takeoff and landing were distinguished by aligning data from the data logger accelerometer against the simultaneous data streams of ICP, mean arterial pressure, and cerebral perfusion pressure. In addition, the CCATT members were asked to note takeoff time, altitude on reaching cruising altitude, and any significant changes in altitude and time of descent. Individual files were reviewed to verify quality of the data.

Selection of Subjects

A convenient sample of patients requiring ICP monitoring and transport from Craig Joint Theater Hospital, Bagram Air Field, Afghanistan, to Landstuhl Regional Medical Center were studied. This study used active duty, activated Reservists, and National Guard/Air National Guard warfighters and U.S. civilians and contractors as subjects. Patients sustaining TBI and subsequently requiring ICP monitoring were evaluated.

Inclusion Criteria

Subjects included in this study were U.S. military personnel, Department of Defense personnel, or civilian contractors eligible for evacuation by the U.S. Air Force aeromedical evacuation system. Subjects had sustained a TBI and had both an external ventricular drainage device and an existing arterial catheter placed for standard care.

Exclusion Criteria

Subjects meeting any of the following criteria were excluded from participation in the study:

–Subjects with TBI without an external ventricular drainage device including those using a Codman pressure monitor.
–Subjects without an existing arterial catheter.
–Detainees or enemies of peace.

RESULTS

The study duration was 6 to 37 hours for each patient. Continuous ICP measurements were recorded and then downloaded and analyzed. The length of the recordings ranged from 467 to 2,273 minutes. The parameters analyzed were instances of ICP > 20 mm Hg and instances of variation of ICP ± 50% of the baseline ICP and the duration of each instance. Baseline ICP was defined as the stable ICP reading after loading patient onto the plane, settling the patient, and zeroing the monitoring equipment. Table I shows the number of instances of ICP > 20 mm Hg (range 0–238 instances) and duration of instances (range 0–3281 seconds). Table II shows the number of instances of ICP ± 50% of the baseline ICP (range 0–921 seconds) and duration of instances (range 0–9054 seconds). The tables also include the total, median, and interquartile ranges (IQRs) of the duration.

TABLE I. Observations of in-theater intracranial pressure (ICP)

Observation No.	Instances	Total Duration (Seconds)	Median (IQR) (Seconds)	Range (Seconds)
1	39	1,151	23 (16–34)	11–95
2	0	0	0	0
3	10	302	13 (12–19)	11–165
4	236	9,445	19 (13–15)	11–1,160
5	3	41	14 (12–15)	12–15
6	0	0	0	0
7	0	0	0	0
8	12	647	17 (13–34)	12–298
9	17	23,514	1,588 (457–2,042)	30–3,281
10	0	0	0	0
11	0	0	0	0

Numbers indicate ICP > 20 mm Hg and patients 2, 6, 7, 10, 11 had no incidents of ICP > 20 mm Hg. IQR, interquartile ranges.

TABLE II. In-theater Intracranial Pressure (ICP) ± 50% of Baseline

Observation No.	Instances	Total Duration (Seconds)	Median (IQR) (Seconds)	Range (Seconds)
1	10	197	18 (16–19)	13–37
2	27	1,6585	48 (31–15)	13–9,054
3	35	914	20 (14–30)	11–146
4	155	4,226	18 (13–30)	11–569
5	921	61,183	23 (17–337)	11–4144
6	36	1,127	24 (15–37)	11–146
7	19	4,028	35 (17–337)	13–1,192
8	10	1,161	49 (16–120)	13–558
9	27	17,208	160 (29–805)	12–2,801
10	6	1,128	99 (25–282)	18–608
11	0	0	0	0

Patient 11 had no instances of ICP ± 50% of baseline ICP. IQR, interquartile ranges.

TABLE III. Instances of Intracranial Pressure (ICP) > 20 mm Hg During a Window of 20 Minutes Before and 20 Minutes After Landing

Observation No.	Instances Takeoff	Duration Takeoff (Seconds)	Instances Landing	Duration Landing (Seconds)
1	0	0	2	41
2	0	0	0	0
3	0	0	1	19
4	0	0	23	2,140
5	0	0	0	0
6	0	0	0	0
7	0	0	0	0
8	9	567	3	80
9	2	1,571	2	1,022
10	0	0	0	0

Patients 2, 5, 6, 7, 10 had no instances of ICP > 20 mm Hg during the defined time period around takeoff and landing. Time of takeoff and landing could not be determined for patient 11.

TABLE IV. Instances of ICP Varying ± 50% of Baseline ICP During a Window of 20 Minutes Before and 20 Minutes After Landing

Observation No.	Instances Takeoff	Duration Takeoff (Seconds)	Instances Landing	Duration Landing (Seconds)
1	0	0	0	0
2	4	317	4	175
3	0	0	1	14
4	2	45	42	1,607
5	1	116	16	605
6	0	0	2	23
7	0	0	4	1,120
8	6	503	0	0
9	4	408	3	334
10	1	608	2	43

Patient 1 had no instances of ICP ± 50% of baseline during the defined time period around takeoff and landing. Time of takeoff and landing could not be determined for patient 11.

Additionally, we examined the supposition that takeoff and landing events would be periods of transport associated with the greatest degree of ICP variability. To achieve this, the data were examined during a period of 20 minutes before and 20 minutes after both takeoff and landing. Takeoff and landing was identified by scrutinizing the continuous accelerometer output for a very characteristic single-axis spike that occurred during these events. The data were evaluated with respect to the same clinical parameters: absolute ICP > 20 mm Hg and ICP variability ± 50 % from baseline ICP (Tables III and IV).

DISCUSSION

The main findings of this study are the following: (1) there were instances of ICPs greater than 20 mm Hg and changes in ICP ± 50% of baseline values during aeromedical transport,

and (2) takeoff and landing were identified as events that produced the greatest alterations in ICP. Although elevations in ICP during aeromedical transport were common, the observational nature of this trial prevents any linkage to these derangements in ICP with changes in outcomes.

TBI claims the lives of more than 56,000 persons in the United States each year, results in hospitalization for another 373,000 persons, and leaves 99,000 persons permanently disabled.[7] The total cost for treatment and rehabilitation of patients with brain injuries is estimated at $48.3 billion annually, and this figure does not include the cost to society of lost years of productivity.[8] Previous studies suggest that secondary insults such as hypoxia and hypotension may worsen a brain injury.[9–19] Recent recognition that secondary brain insults are primary determinants of outcome for severely brain-injured patients has heightened emphasis on preventing these secondary insults. However, the data in most previous studies on this topic are either registry based or retrospective or include only secondary insults that occur in the intensive care unit setting. Most prior investigations have provided limited information on secondary insults occurring during transport.

Stresses of Flight

Aeromedical transport because of altitude and flight physiology presents unique challenges when caring for patients. The additional stresses presented by this environment many have effects on patient conditions and comfort during transport. The effect of hypobarism may be demonstrated by increasing pressure and pain in the ear, sinuses, gastrointestinal tract, respiratory system, and malfunctioning of medical equipment because of effect of Boyle's law. Decompression sickness may result because of dissolved gases in the blood being released. Hypoxemia at altitude may require more oxygen to maintain adequate arterial saturation as a result of decreased partial pressure of oxygen at altitude. The effects of hypobarism increase with decreased cabin pressure. Aeromedical transport is often accomplished using military cargo planes that provide excess noise and vibration during flight. Hearing protection for patients and flight crew is required to avoid damage. Vibration experienced during flight is unavoidable and may make an already uncomfortable patient more so. Padding of the litter and positioning and placing the patient toward the middle of the air frame away from the fuselage may decrease vibration. Gravitational forces during takeoff, landing, and during flight may have a negative effect on blood pressure and ICP. Positioning of the patient is crucial to mitigating these effects. Dehydration because of extremely dry air at altitude and dry gases used in ventilated patients must be monitored. Additional fluids may be required to offset the effects of flight on hydration. All of the stressors of flight on the patient must be monitored and treated or prevented if possible all while the caregiver is experiencing the same effects, making for a difficult environment.[20,21]

Effects of Aeromedical Transport on TBI

The increasing prevalence of TBI is a recognized phenomenon in the current theaters of Operations Iraqi Freedom and Enduring Freedom. This is a reflection of the increasing exposure of combatants to improvised explosive devices and other explosive ordnances. The resultant injury patterns take the form of either blunt force trauma or direct penetrating intracranial injuries. These injuries result in cellular trauma and resultant edema of central nervous system tissue within the closed confines of the cranial vault. The ability to establish and maintain an appropriate assessment of the ICP of a TBI patient is fundamental of care for these injured soldiers. The tactical and austere setting of combat medicine makes the precise measurement and monitoring of ICP an even more daunting task.

Presently, the options for neurologic monitoring available to CCATTs for aeromedical transportation do not permit dynamic assessment of ICP during critical aspects of the flight (i.e., takeoff and landing). In best-case scenarios, ICP is manually recorded at intervals by medical personnel and CCATT members. Knowledge regarding changes in ICP during the evacuation process may serve as the basis for future development of more effective en route care equipment, improve the training of aeromedical evacuation providers, and improve overall patient safety in both the military and civilian setting. The ability to longitudinally monitor ICP data throughout a CCATT mission provides awareness of potentially significant events that occur during ground transportation, tactical takeoff and landing, and care at altitude. This "first-of-its-kind" study provides groundbreaking visibility regarding the scope of ICP issues in the combat casualty with TBI and propose potential medical solutions.

The sample size here is small owing to the nature of research in the midst of conflict and care of critically ill patients, but the data show that patient movement in the aeromedical environment can cause large fluctuations in ICP values and possible untoward effects on patients' conditions. Fluctuations in ICP appeared to be less extreme than anticipated, possibly because of use of higher sedation doses and the hemicraniectomy that most casualties received before being transported, although the length of transport produced more incidences of ICP derangement. Takeoff and landing are arguably the points in the transport that would affect ICP to the greatest degree. Acceleration during takeoff produces the greatest physiologic stress on the body. To mitigate the impact of acceleration, the casualties are loaded on the aircraft head first with the head of bed elevated at least 30°. Landing tends to be a more gradual deceleration but can be associated with significant turbulence and produce bouncing of the litter up to 6 inches or more, which could affect ICP and blood pressure. Figures 2 and 3 show the accelerometer data that depict movement of the airframe (top graph) and associated ICP (bottom graph) during two aeromedical flights. As illustrated by these two graphs, ICP varies considerably in the first example, whereas the other is less affected by the flight.

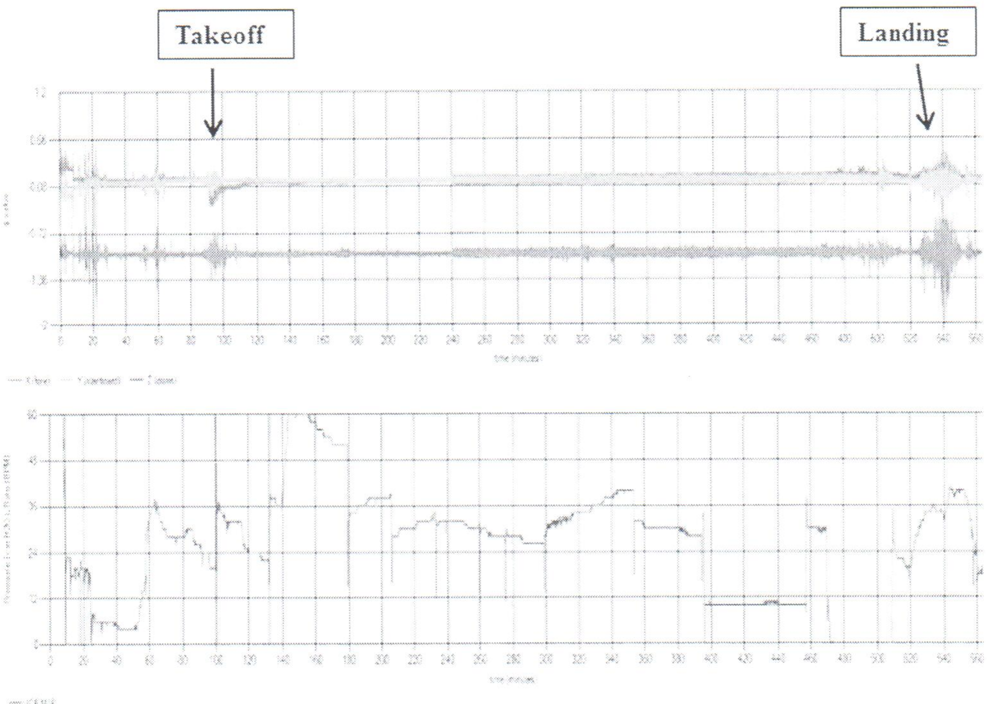

FIGURE 2. In-theater movement intracranial pressure measurement.

Evaluation of the data regarding ICP variability during takeoff and landing events provided interesting insight to the en route care transport of the patient with TBI. The authors had originally speculated that takeoff and landing would provide a great deal of ICP stress secondary to accelerative and decelerative forces. In addition, the noise, vibration, and patient agitation associated with the tactical takeoff and landing of military cargo planes is significant.

Although the data in Tables III and IV suggest that this is the case in some patients, it does not appear to be an important clinical marker for all patients. We did, however, note large increases in ICP at takeoff in a small number of patients. The variability in ICP is marked in some patients but also noticeably absent in others. This variability may reflect the level of sedation and/or adequacy of a previous craniectomy. Further data acquisition will be required to address this issue.

If one compares the variability in ICP across the entire duration of transport to the specific windows of takeoff and landing, the average ICP variability does not appear to be different during the takeoff and landing periods.

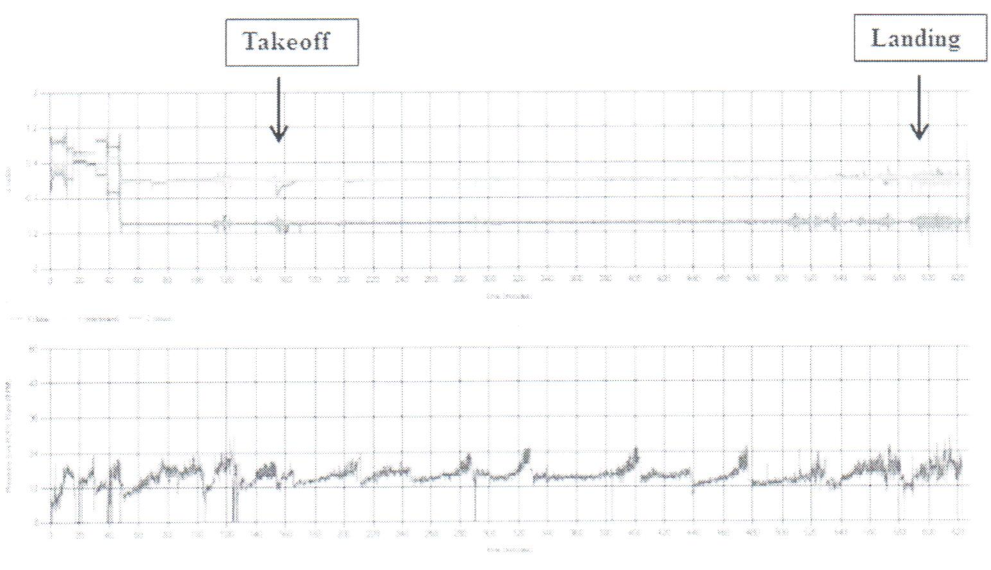

FIGURE 3. In-theater movement intracranial pressure measurement.

LIMITATIONS

Because the study was observational in nature, the medical records of the patients transported were unavailable to the study team. As such, we were unable to determine what interventions occurred or the lack of intervention, and/or under what circumstances any interventions were made and the subsequent effect on patients' ICP. In-flight interventions including sedation, draining of the ventricular space, mechanical ventilation, level of awareness, and pharmacologic therapy likely impacted ICP during flight, but there was no method to match these interventions to the ICP and blood pressure recordings. We were also unable to determine which patients had undergone a therapeutic craniectomy to relieve intracranial hypertension before transport. To determine outcome differences, larger studies that include in-flight records as well as outcome data must be done.

CONCLUSION

Transport of patients suffering from TBI either by aeromedical transport or by ground can produce adverse effects to ICP. Although extremely invasive, patients having had a hemicraniectomy before and sedation during aeromedical transport appeared to produce less drastic than expected increases in ICP. It is unclear what effect the smaller fluctuations in ICP (±50% of baseline, but < 20 mm Hg) had on patient outcome. Observational research in theater, to allow an understanding of the current state-of-the-art care is critical to identifying problems and altering treatment to improve care. Future in-theater research mandates the collection of patient-specific interventions and identifiers in order for us to understand the physiologic consequences of aeromedical transport.

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